Effect of calibration errors on cosmological parameter estimates

Dragan Huterer
University of Michigan

with:
Carlos Cunha (Stanford), Wenjuan Fang (Michigan)

Preliminary results of ongoing work.
Comments are welcome.

Summary of talk

I created an end-to-end pipeline to propagate arbitrary calibration errors into cosmological parameter biases

Summary of findings:

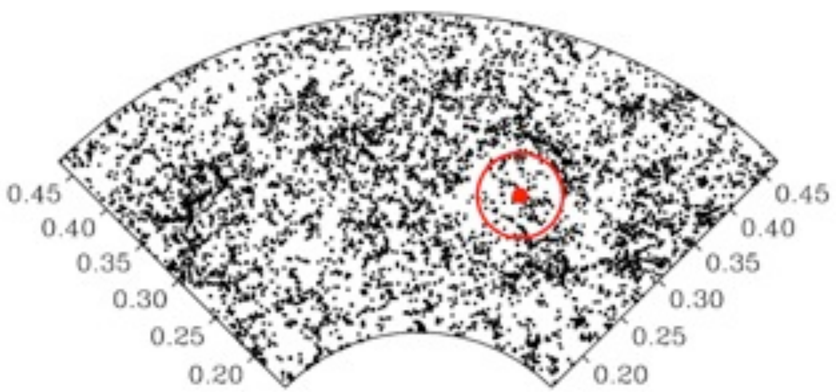
1. Calibration *breaks statistical isotropy* of LSS signal (obvious in retrospect)

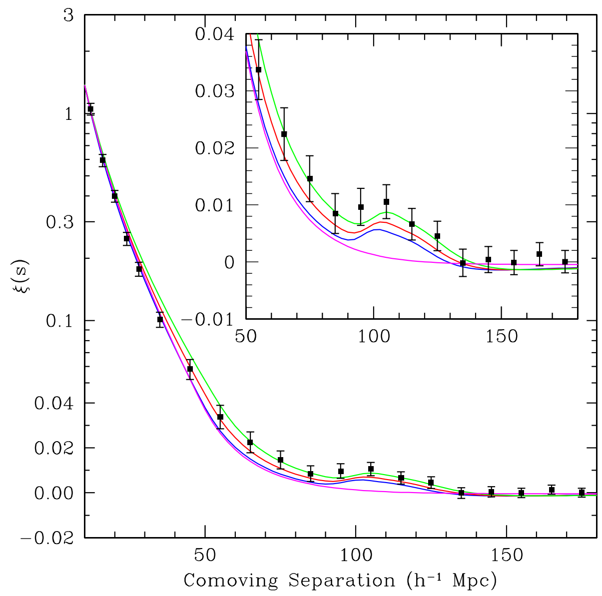
2. *Large-angle* errors beyond the monopole - dipole, quadrupole, etc - are most damaging

3. Control at level << 0.1% might be required for DES-type survey and beyond

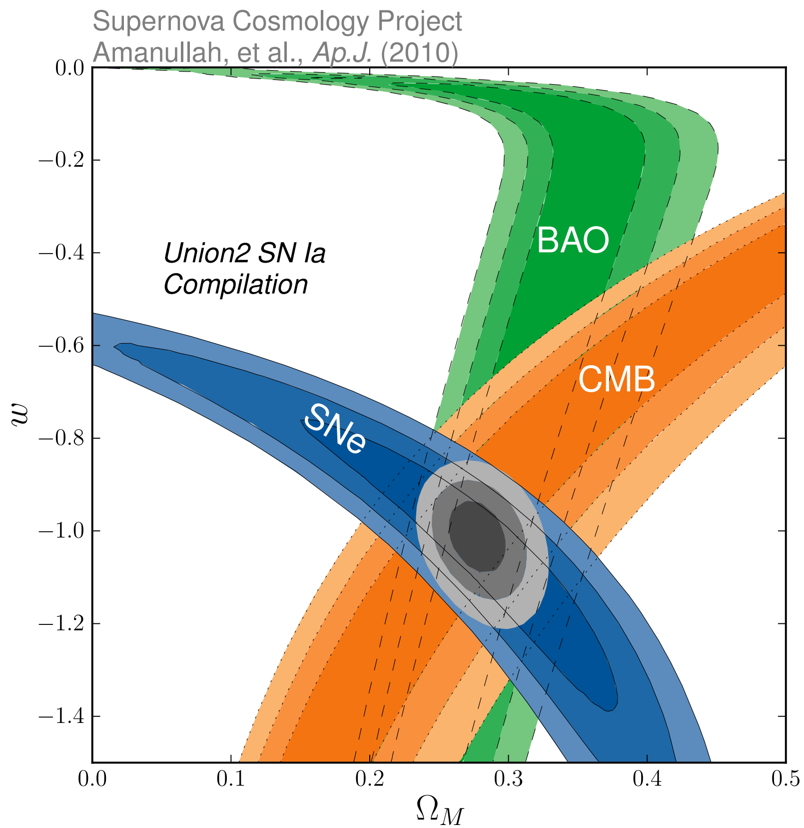
Scientific Motivation:

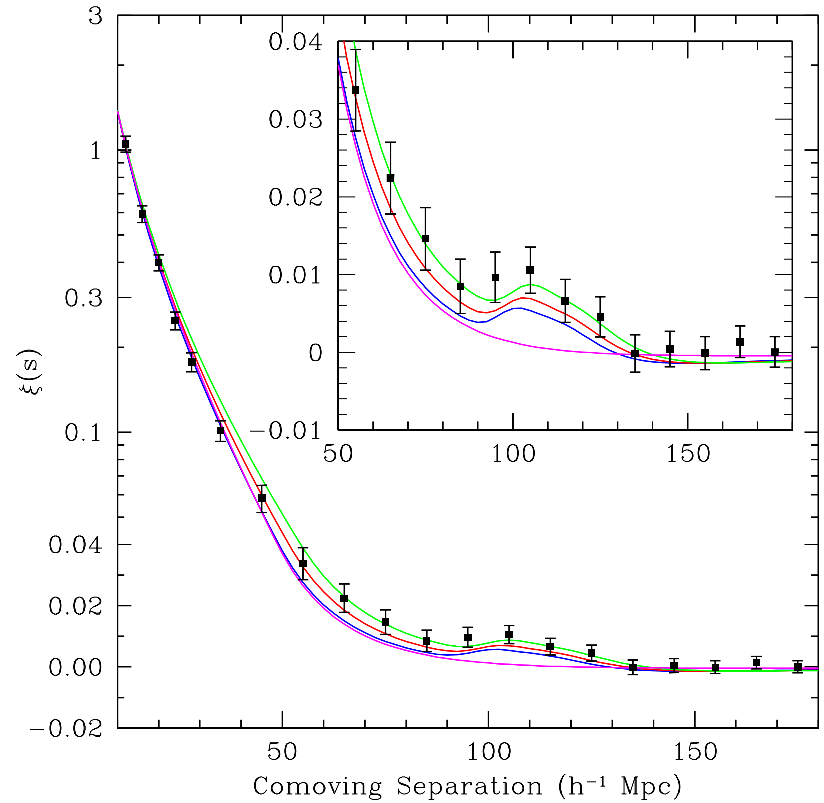
why control calibration in **LSS** measurements





Science motivation #1: dark energy





from type Ia supernovae

(e.g. Amanullah et al 2010)

~0.01 mag calibration required

or

from galaxy clustering

(e.g. Eisenstein et al 2005)

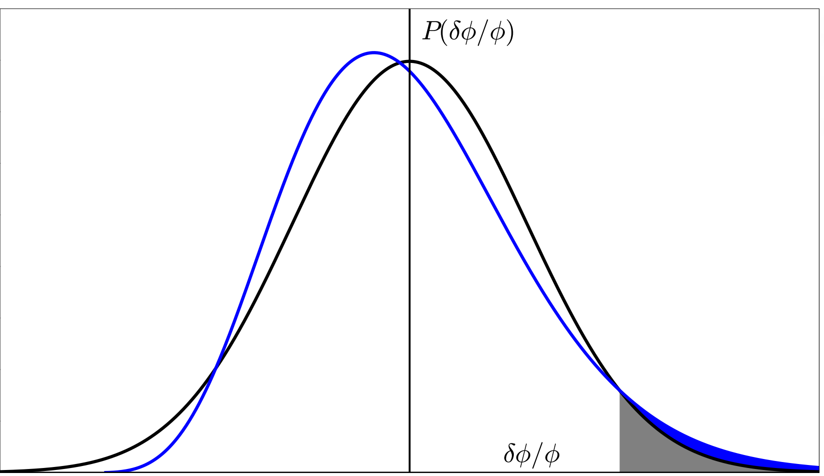
⇒ this work

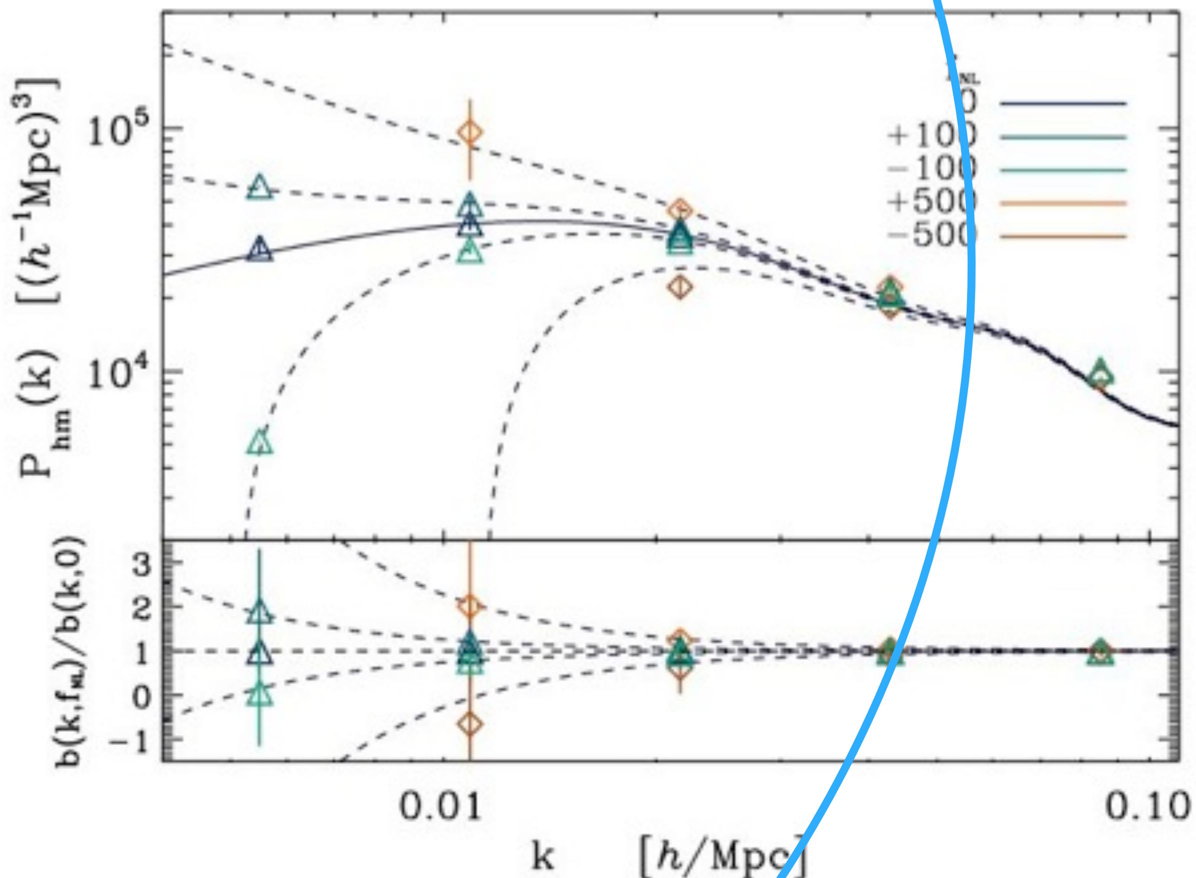
Science motivation #2: primordial non-Gaussianity

Scale dependence of non-Gaussian halo bias:

$$P_h(k,z) = b^2(k,z)\, P_{\rm DM}(k,z)$$

Constraints already **500×** better than this departure from Gaussian:

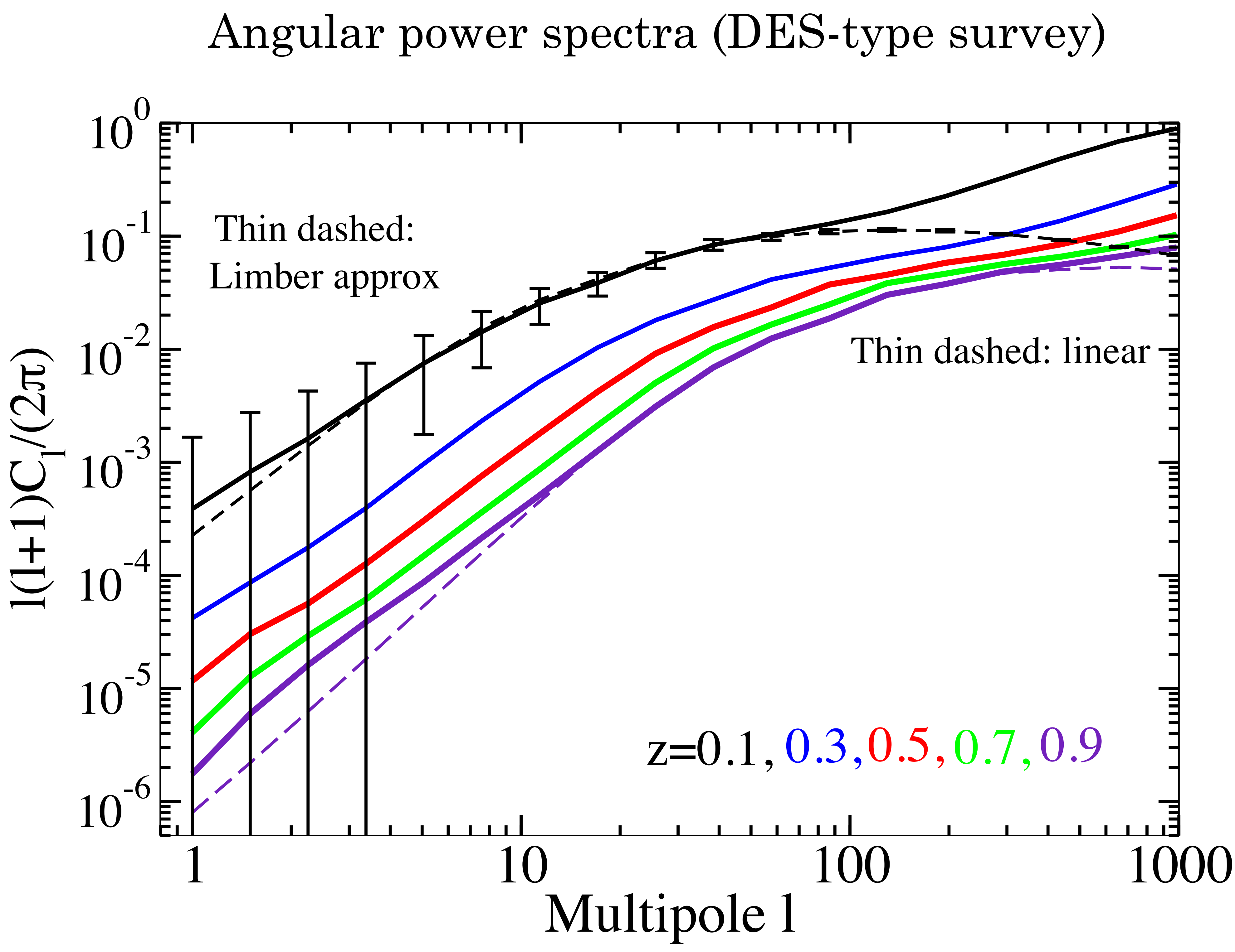




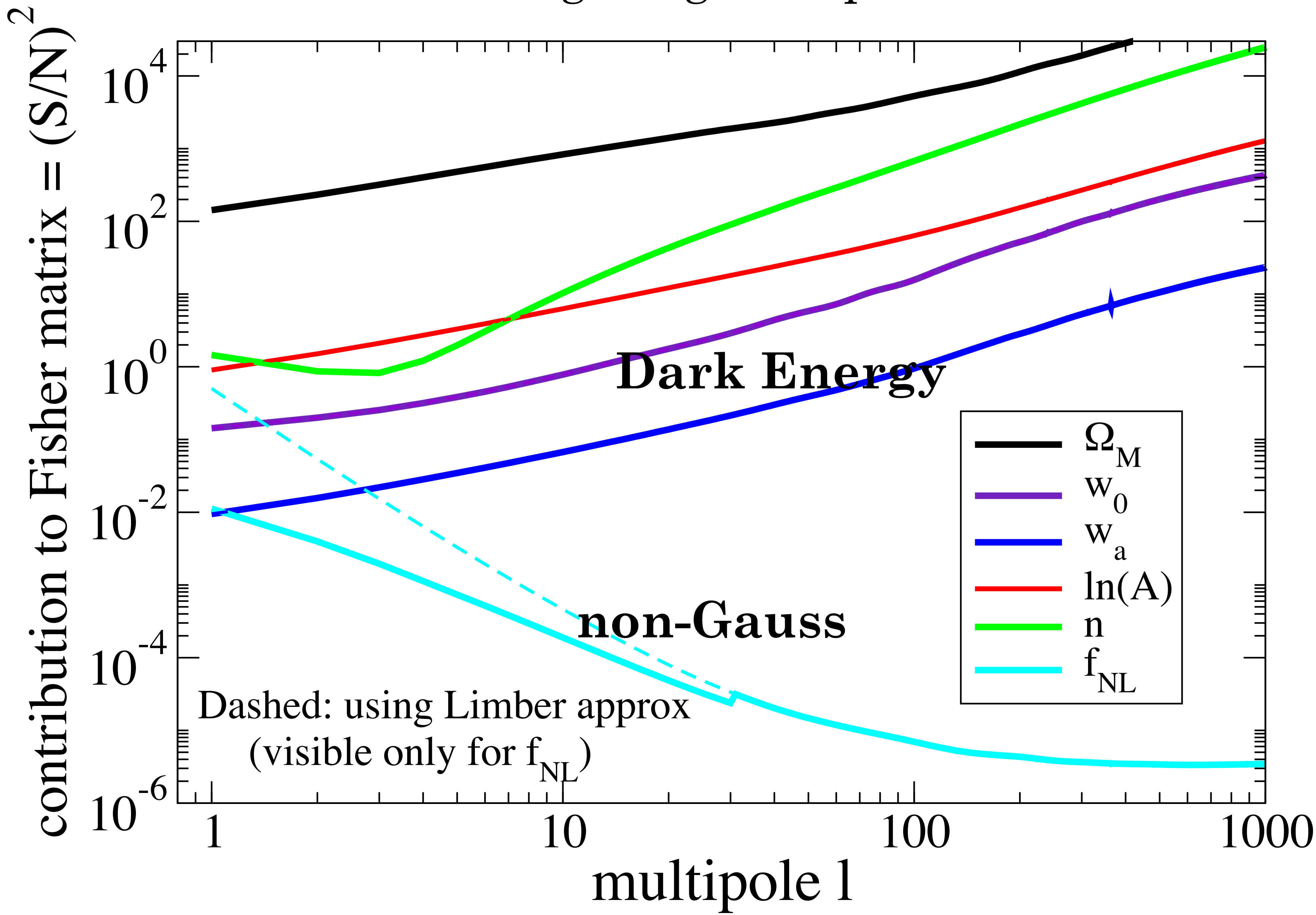
$$b(k) = b_{\rm G} + f_{\rm NL}\,\frac{\rm const}{k^2}$$

Current constraints on $f_{\rm NL}$ from LSS (SDSS) are comparable to those from WMAP!

Dalal, Doré, Huterer & Shirokov 2008


Angular power spectra (DES-type survey)
Thin dashed: Limber approx
Thin dashed: linear
z=0.1, 0.3, 0.5, 0.7, 0.9
$l(l+1)C_l/(2\pi)$
Multipole l
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
10
100
1000

Non-Gaussianity constraints are special: come from large angular/spatial scales



Review of harmonic description

$$\frac{\delta T}{T}(\theta,\phi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta,\phi)$$

Assuming statistical isotropy:

$$\langle a_{\ell m} a^*_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} C_\ell$$

Getting the a_{lm} from observed sky is trivial:

$$(a_{\ell m})^{\rm cut} = \int_{\rm obs.\,sky} \frac{\delta T}{T}(\theta,\phi)\, Y^*_{\ell m}(\theta,\phi)\, d\Omega$$

But reconstructing full-sky pattern from cut-sky observations is very hard:

$$(a_{\ell m})^{\rm cut} = \sum_{\ell' m'} M_{\ell\ell' mm'} (a_{\ell' m'})^{\rm full} \quad \Rightarrow \quad \mathbf{a}^{\rm full} = \mathbf{M}^{-1} \mathbf{a}^{\rm cut}$$

poorly behaved inversion

Approach to modeling calibration errors and results

(True) Galaxy density field:

$$\frac{N(\hat{\mathbf{n}}) - \bar{N}(\hat{\mathbf{n}})}{\bar{N}(\hat{\mathbf{n}})} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

Calibration defined:

$$N_{\rm obs}(\hat{\mathbf{n}}) = c(\hat{\mathbf{n}}) N(\hat{\mathbf{n}})$$

Calibration expanded in spherical harmonics:

$$c(\hat{\mathbf{n}}) = 1 + \sum_{\ell m} c_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

Statistical properties of two fields:

$$\langle a_{\ell m} \rangle = 0; \quad \langle a_{\ell m} a^*_{\ell m} \rangle = \delta_{mm'} \delta_{\ell\ell'} C_\ell$$

$$\langle c_{\ell m} \rangle = c_{\ell m}; \quad \langle c_{\ell m} c^*_{\ell m} \rangle = |c_{\ell m}|^2$$

Defining the observed overdensity: t_{lm} coefficients

$$\delta^{\rm obs}(\hat{\mathbf{n}}) \equiv t(\hat{\mathbf{n}}) = \sum_{\ell m} t_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

Final result for the **observed** power spectrum is:

$$\langle t_{\ell m} t^*_{\ell' m'}\rangle = \frac{1}{(1+\epsilon)^2}\left\{\underbrace{\delta_{mm'}\delta_{\ell\ell'}C_\ell}_{\text{isotropic}} + \underbrace{\left[U^{\ell\ell'}_{mm'}\,C_{\ell'} + (U^{\ell\ell'}_{mm'})^*\,C_\ell\right] + \sum_{\ell_2 m_2} U^{\ell_2\ell}_{m_2 m}(U^{\ell_2\ell'}_{m_2 m'})^*\,C_{\ell_2} + c_{\ell m}c^*_{\ell' m'}}_{\text{breaks statistical isotropy}}\right\}$$

Cancels effects of calibration monopole

True power

Calibration (biases)

where $U^{\ell_2\ell}_{m_2 m} \equiv \sum_{\ell_1 m_1} c_{\ell_1 m_1} R^{\ell_1\ell_2\ell}_{m_1 m_2 m}$

$$R^{\ell_1\ell_2\ell}_{m_1 m_2 m} \equiv (-1)^m\sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2\ell+1)}{4\pi}}\begin{pmatrix}\ell_1 & \ell_2 & \ell\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\ell_1 & \ell_2 & \ell\\ m_1 & m_2 & -m\end{pmatrix}$$

Comments on approach

- Expression on previous page is a numerical headache to evaluate - dependences on l, m, l', m', l'', m'' means naively $\mathbf{10^{18}}$ array elements (for $l \leq 1000$) $\rightarrow$ lots of tricks used for speed-up

- This work: assume measurements of isotropic part of power, i.e. $T_l \equiv \langle |t_{lm}|^2 \rangle$, and treat T_l-C_l as bias in observable

- Future work: use "off-diagonal" $\langle t_{lm}\, t_{l'm'} \rangle$ to *internally correct* for the calibration errors (self-calibrate!)

From biases in observables to biases in cosmological parameters

$$\delta p_i = \sum_j (F^{-1})_{ij} \sum_{\ell,b} \frac{\partial C_{bb}(\ell)}{\partial p_j} \frac{1}{\sigma^2_{C_{bb}(\ell)}} \delta C_{bb}(\ell)$$

cosmological parameter bias

covariance (Fisher^{-1}) matrix

sensitivity of obs wrt parameter

error in observable

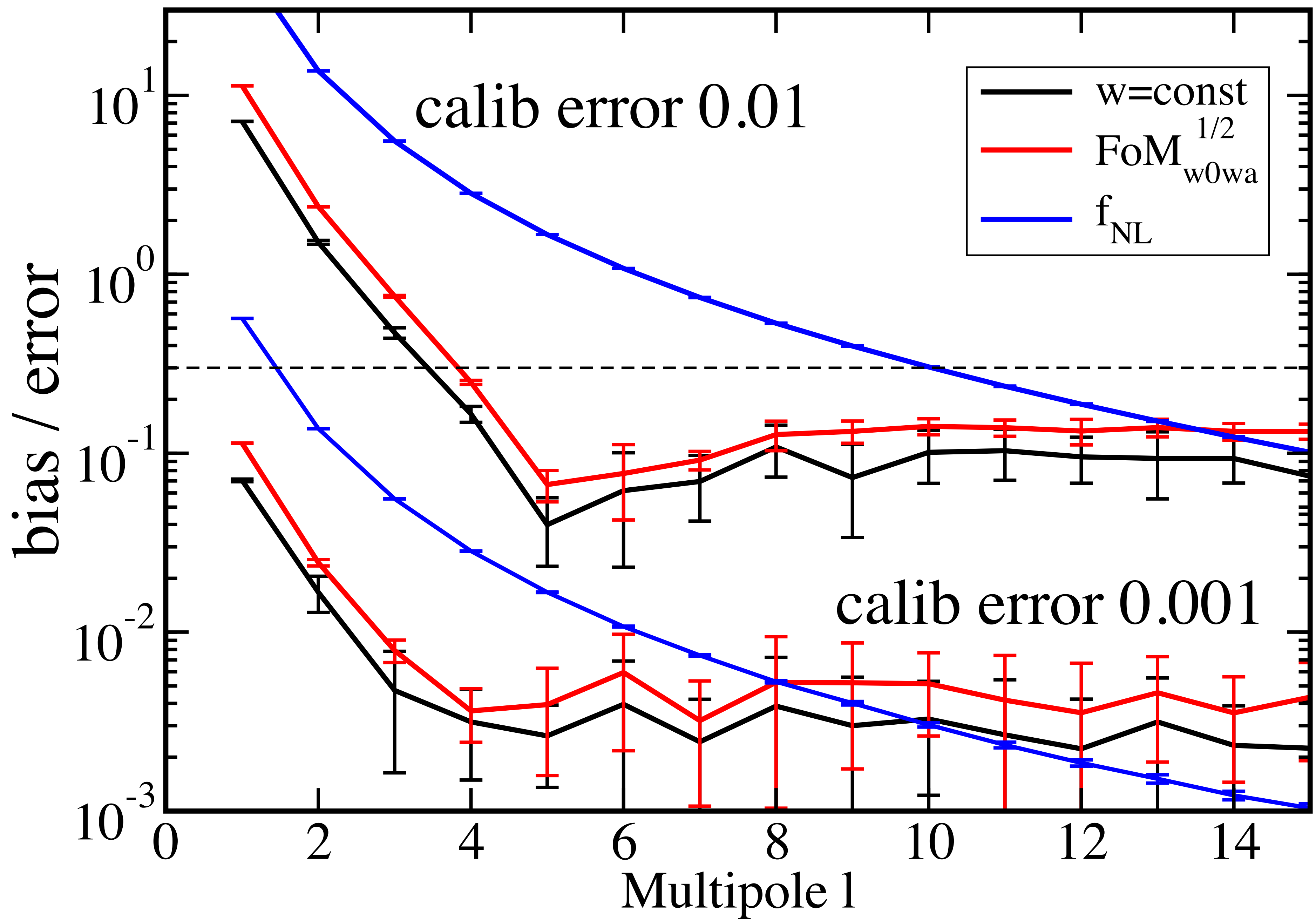
bias in observable

General guideline:

biases have to be much less than statistical errors:

$$\delta p_i << (F^{-1})_{ii}$$

Bias/error ratios per calib error in *single* multipole



Moreover, this implies even more stringent requirements in magnitudes

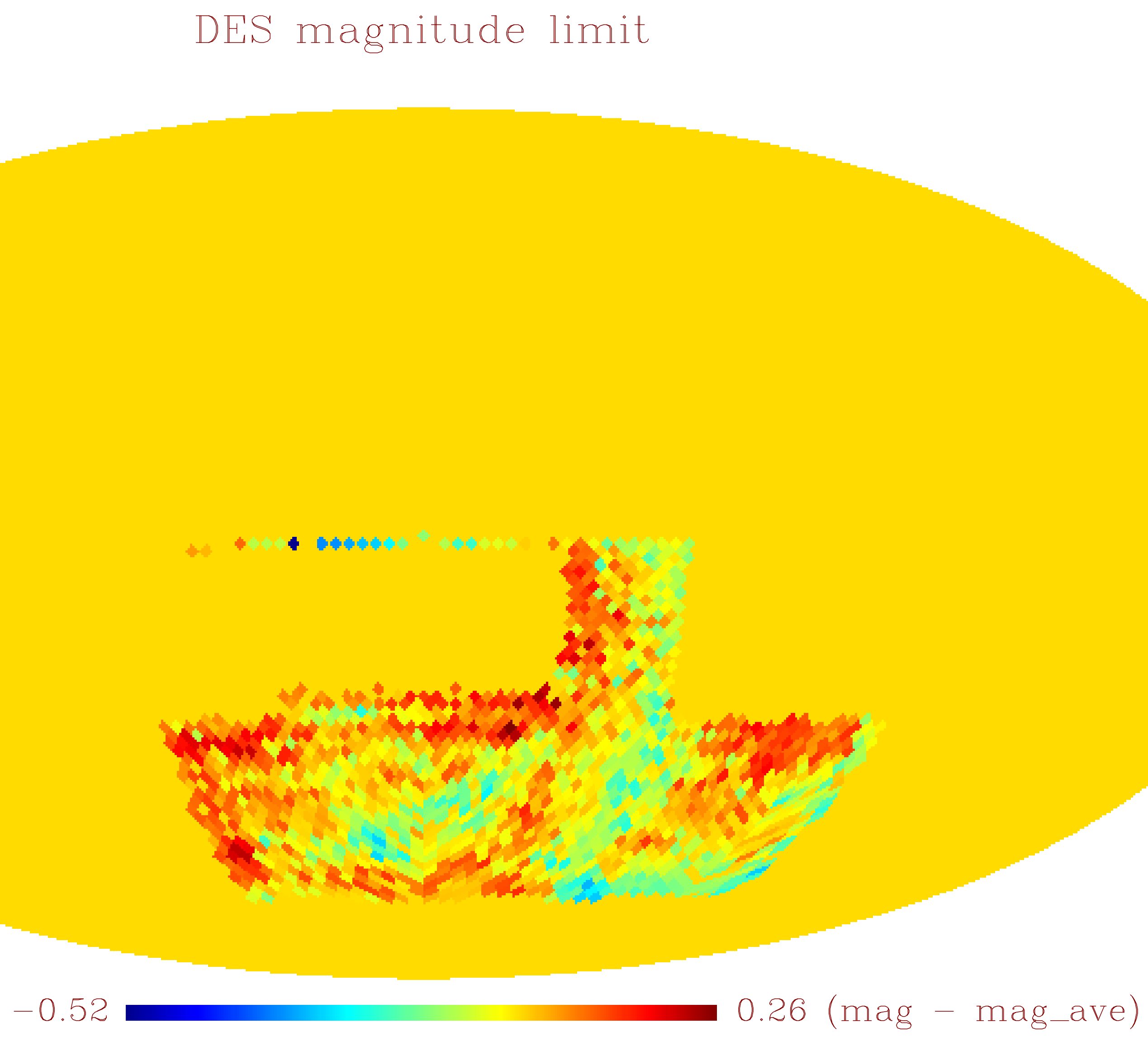
$$\frac{\delta N}{N}(\hat{\mathbf{n}}) \equiv c(\hat{\mathbf{n}}) - 1 \quad = \quad \ln(10) s(z) R\, \delta(E_{B-V})(\hat{\mathbf{n}})$$

$$\sim \quad O(10) \times \delta(E_{B-V})(\hat{\mathbf{n}})$$

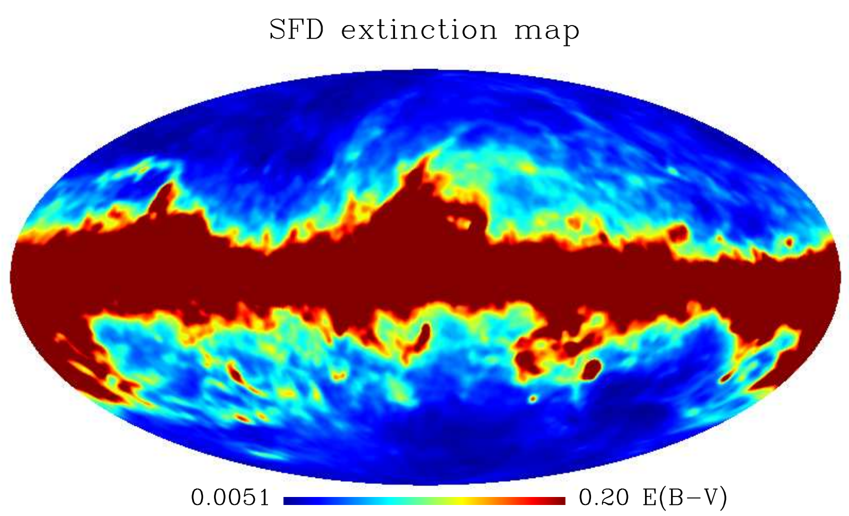
what I called 'calibration error' on previous slide

where

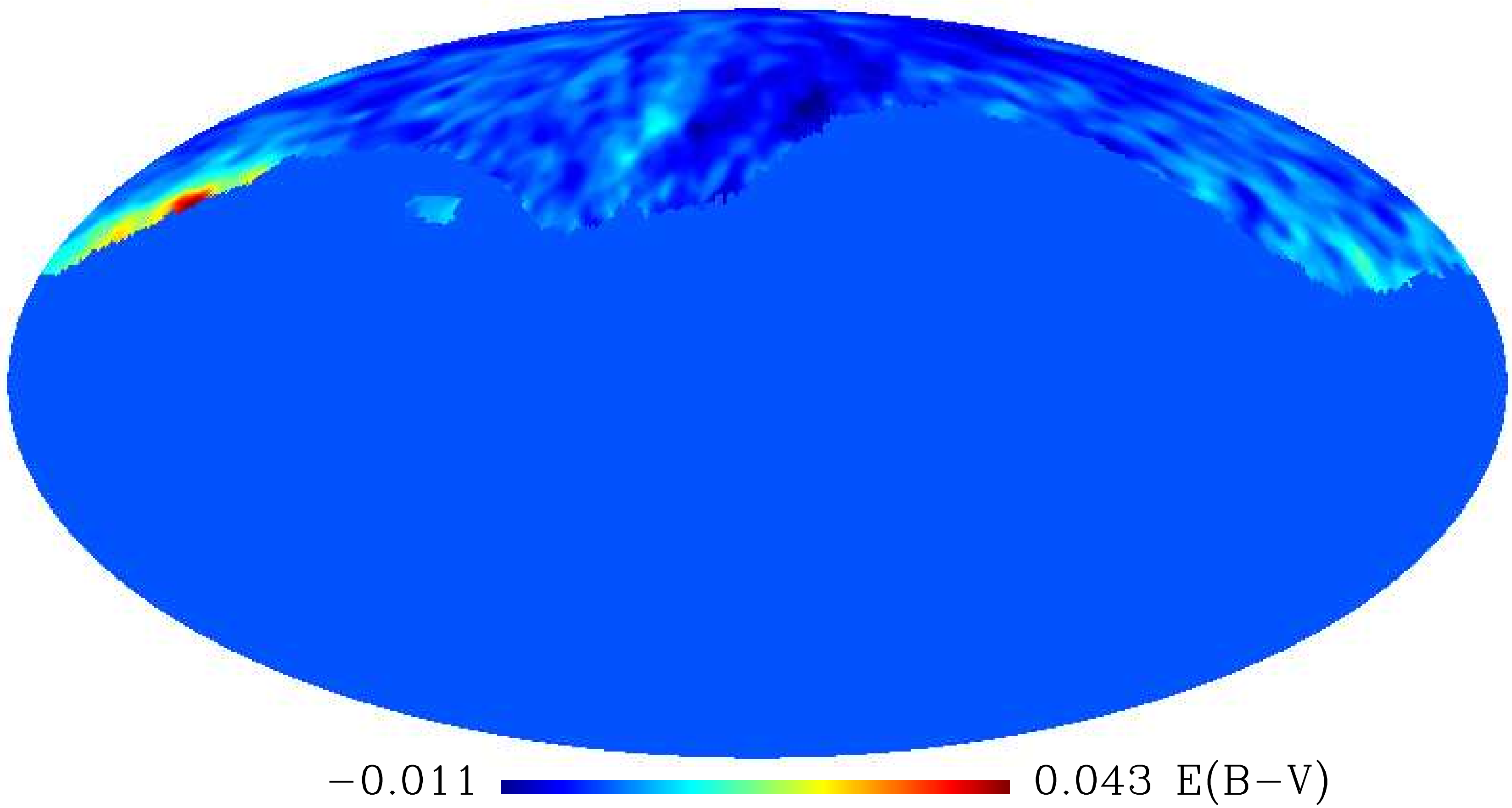
$$s(z) \equiv \left. \frac{d \log_{10} n(z, > m)}{dm} \right|_{m_{\max}}$$



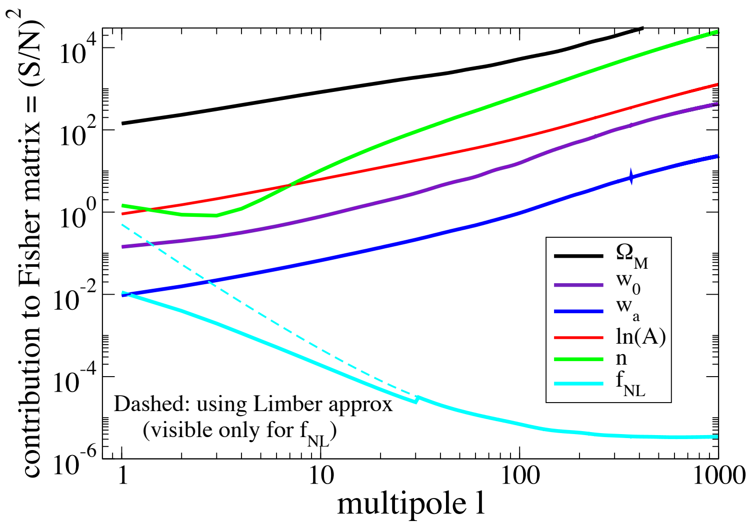
Jim Annis

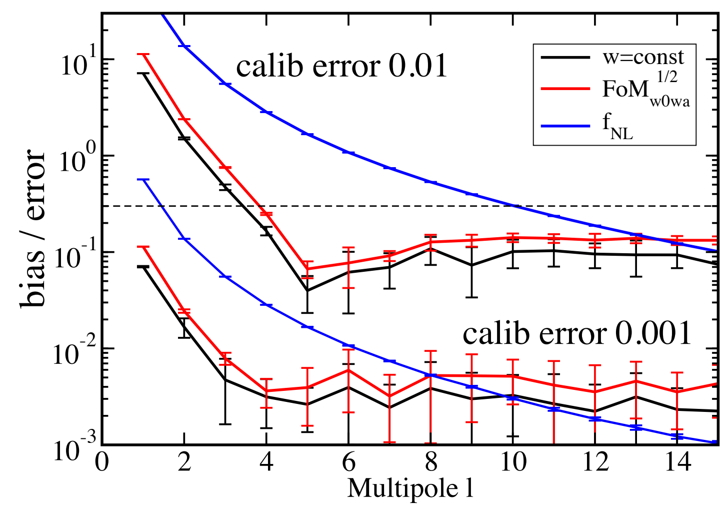


Peek–Graves 2010 corrections to SFD extinction map



Summary of findings





1. Calibration *breaks statistical isotropy* of LSS signal - of the galaxy power spectrum, e.g.

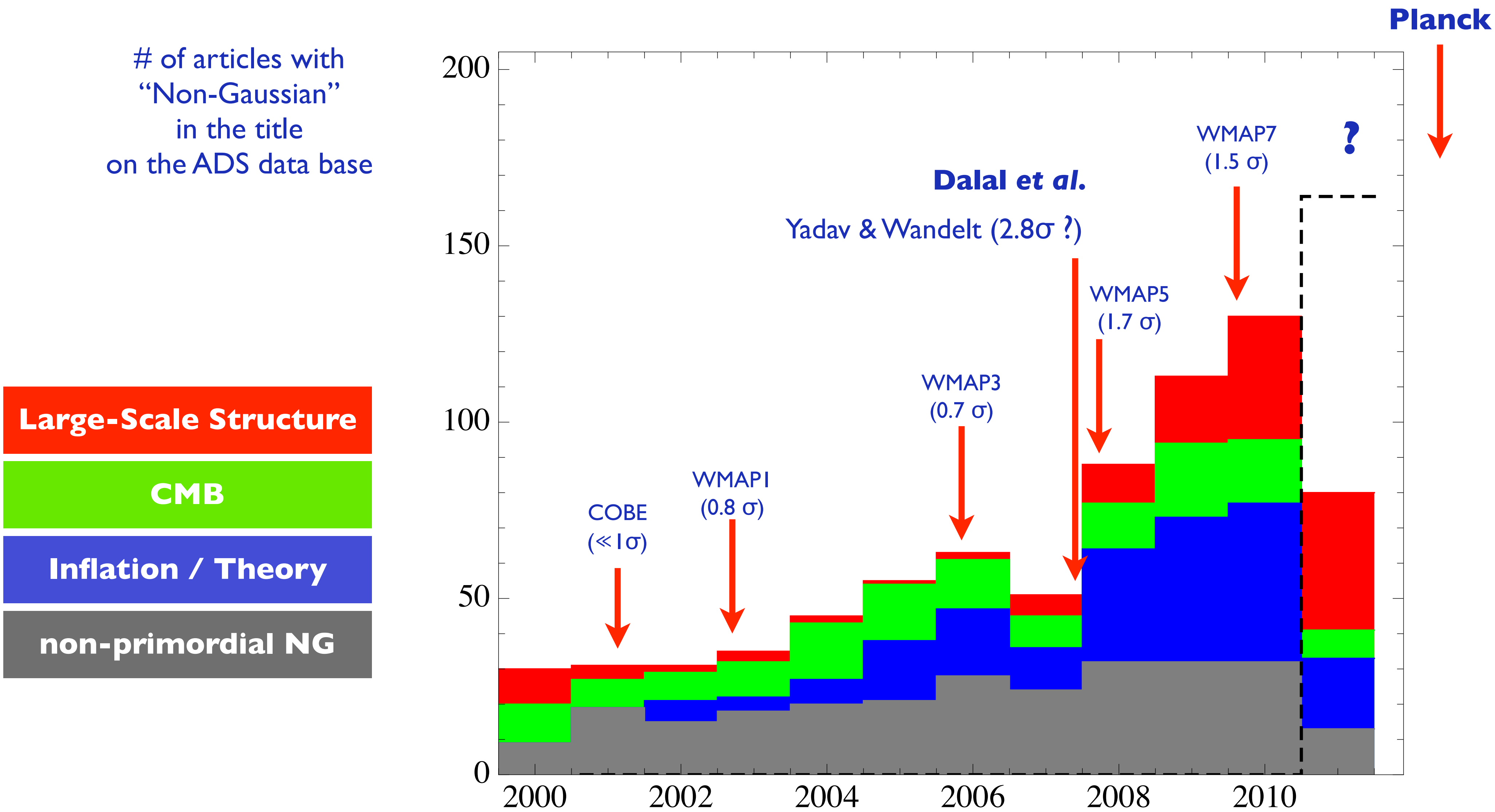
2. *Large-angle* errors beyond the monopole - dipole, quadrupole, etc - are most damaging

3. Control at level <<0.1% may be required for DES-type survey and beyond; higher requirements for NG than for dark energy

Backup slides

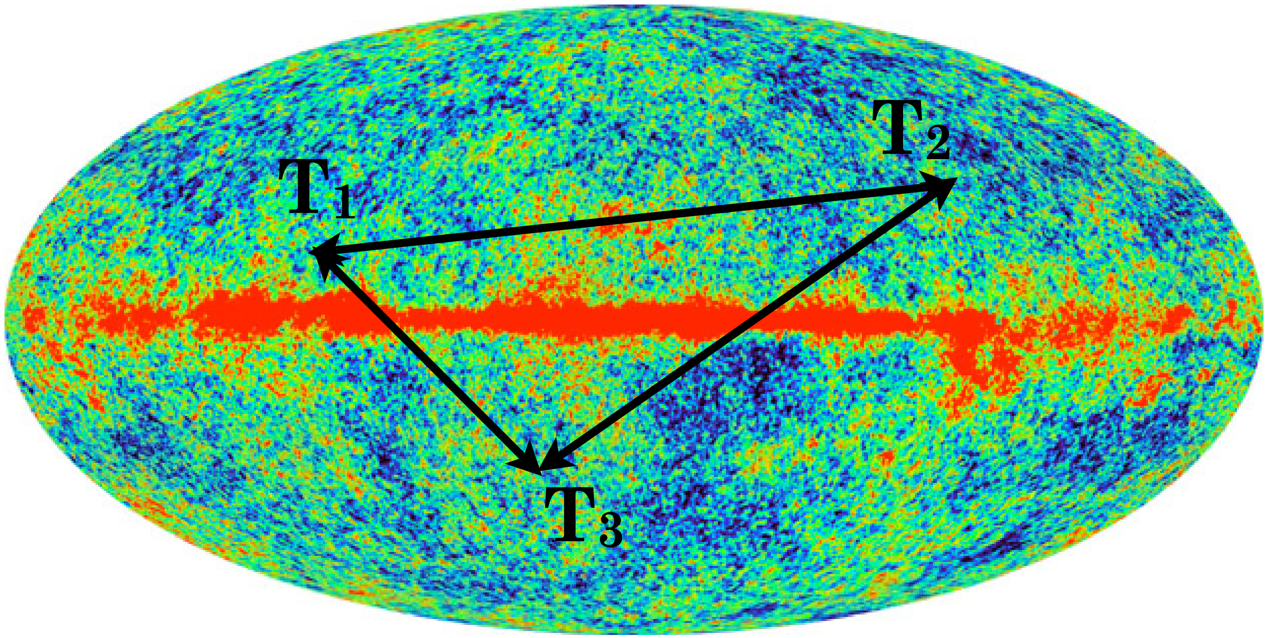
Non-Gaussianity papers in the past 10 years

of articles with
"Non-Gaussian"
in the title
on the ADS data base



Produced by Emiliano Sefusatti

NG from 3-point correlation function



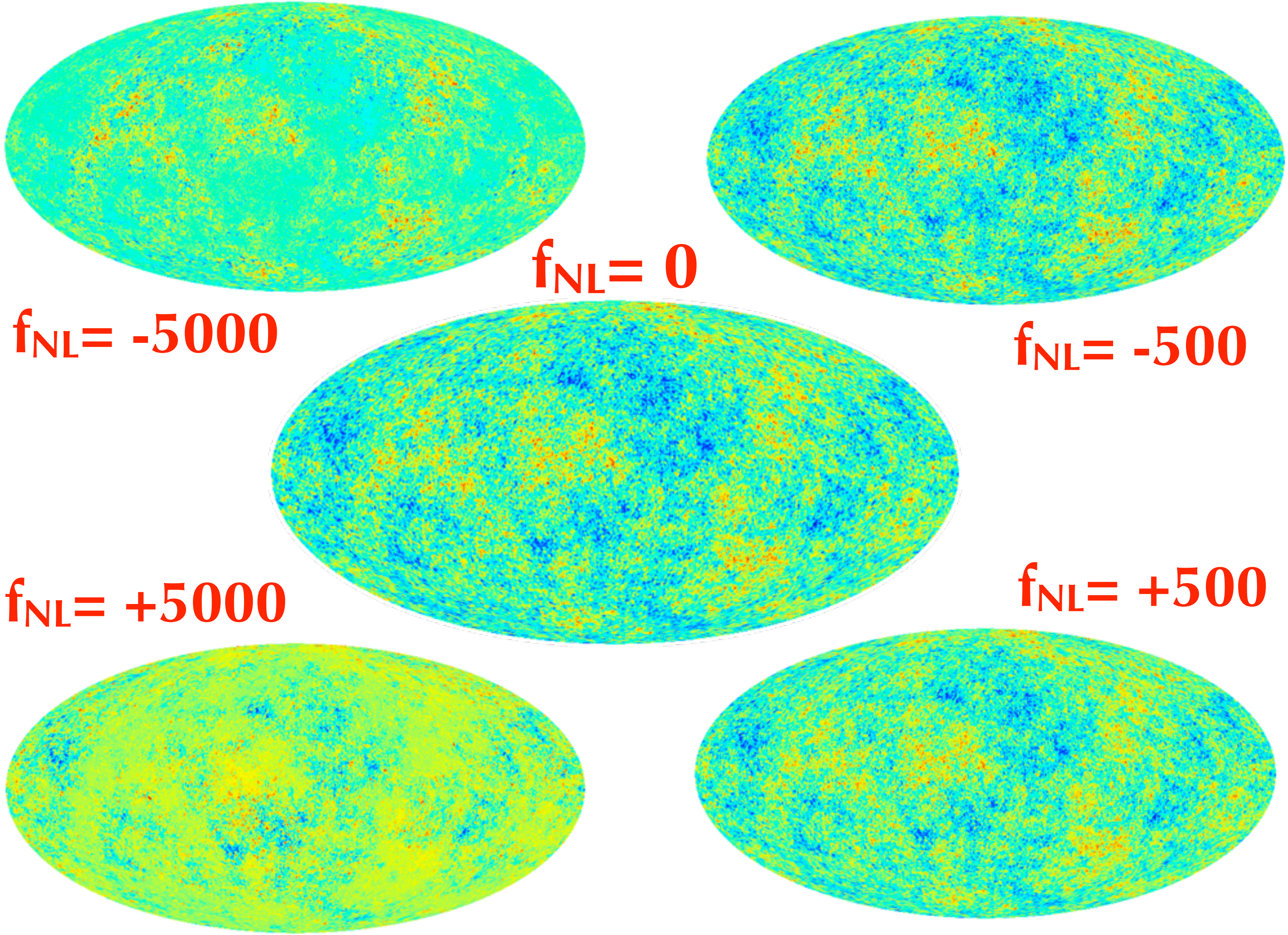
Commonly used "local" model of NG

$$\Phi = \Phi_G + f_{\rm NL} \left(\Phi_G^2 - \langle \Phi_G^2 \rangle \right)$$

Then the 3-point function is related to $f_{\rm NL}$ via (in k-space)

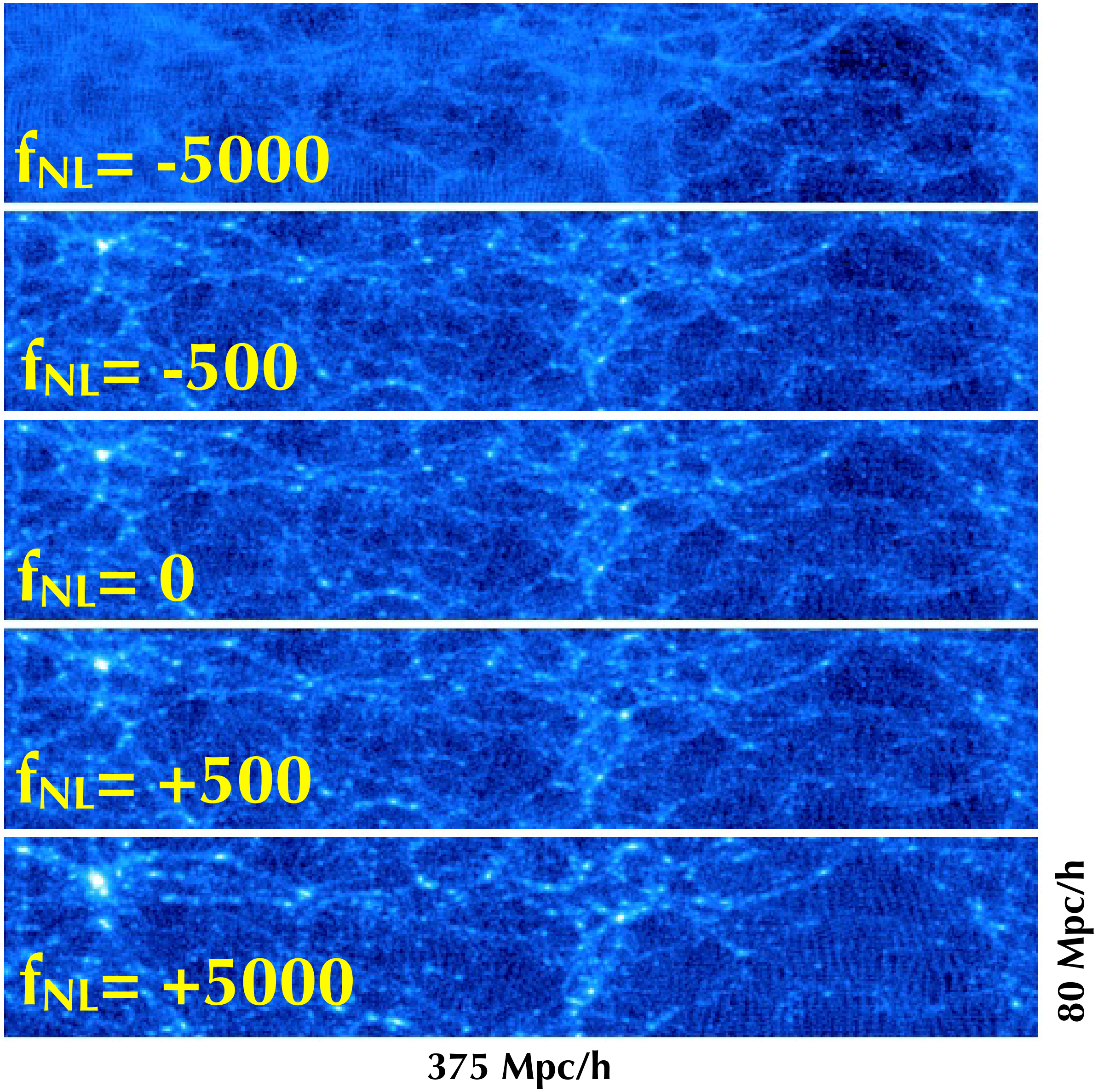
$$B(k_1, k_2, k_3) \sim f_{\rm NL} \left[P(k_1) P(k_2) + \text{perm.} \right]$$

Using publicly available NG maps by Elsner & Wandelt



Current constraint from WMAP: f_{NL}=32±21

Simulations with non-Gaussianity (f_{NL})



- Under-dense region evolution decrease with f_{NL}
- Over-dense region evolution increase with f_{NL}

- Same initial conditions, different f_{NL}
- Slice through a box in a simulation $N_{part}=512^3$, L=800 Mpc/h

Dalal, Doré, Huterer & Shirokov, PRD 2008

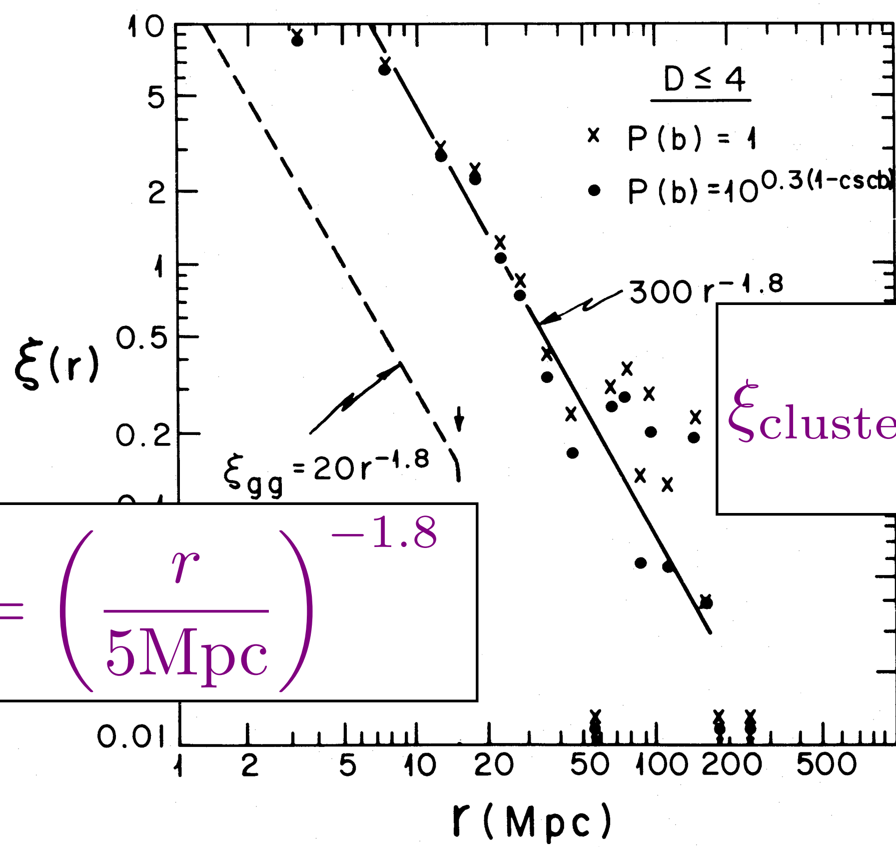
Does galaxy/halo bias depend on NG?

cosmologists measure

$$\text{bias} \equiv \frac{\text{clustering of galaxies}}{\text{clustering of dark matter}} = \frac{\left(\frac{\delta\rho}{\rho}\right)_{\text{halos}}}{\left(\frac{\delta\rho}{\rho}\right)_{\text{DM}}}$$

usually nuisance parameter(s)

theory predicts



$$\boxed{\xi_{\text{galaxies}}(r) = \left(\frac{r}{5\text{Mpc}}\right)^{-1.8}}$$

$$\boxed{\xi_{\text{clusters}}(r) = \left(\frac{r}{25\text{Mpc}}\right)^{-1.8}}$$

Bahcall & Soneira 1983

Bias of dark matter halos

$$P_h(k,z) = \boxed{b^2(k,z)}\, P_{\rm DM}(k,z)$$

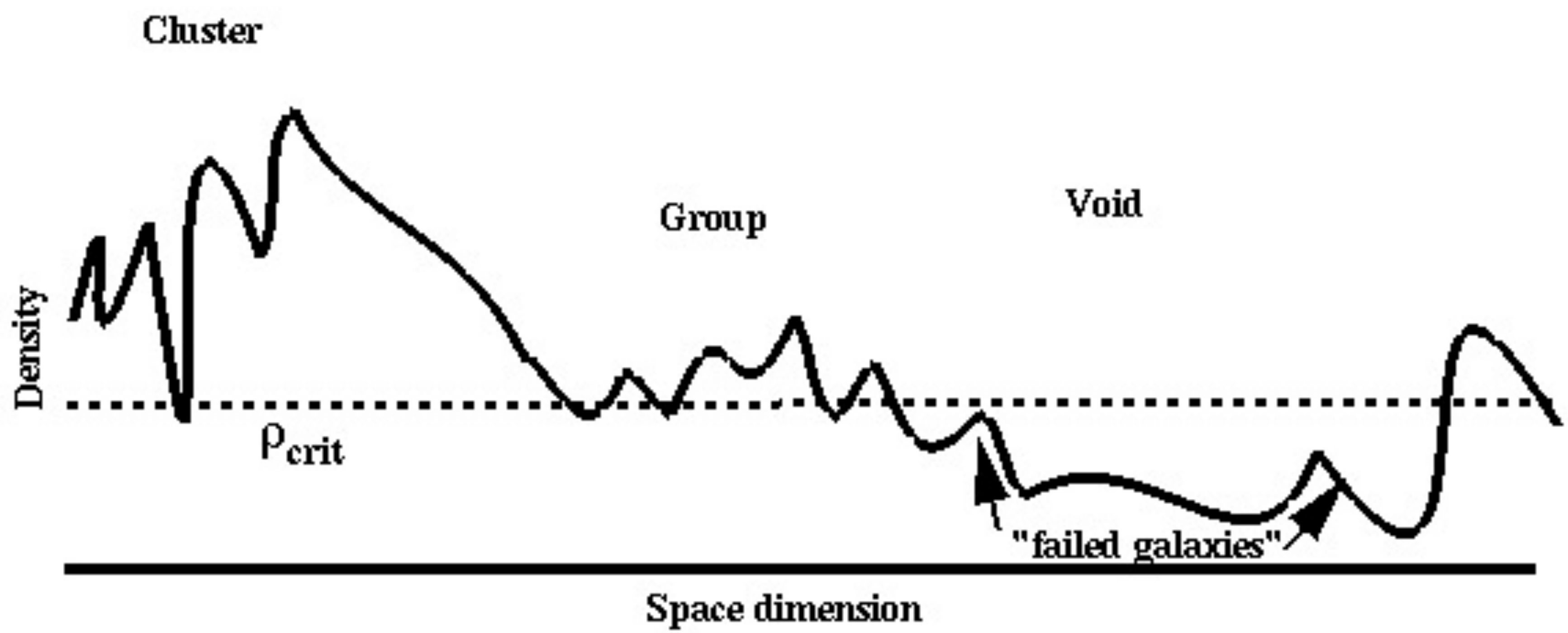
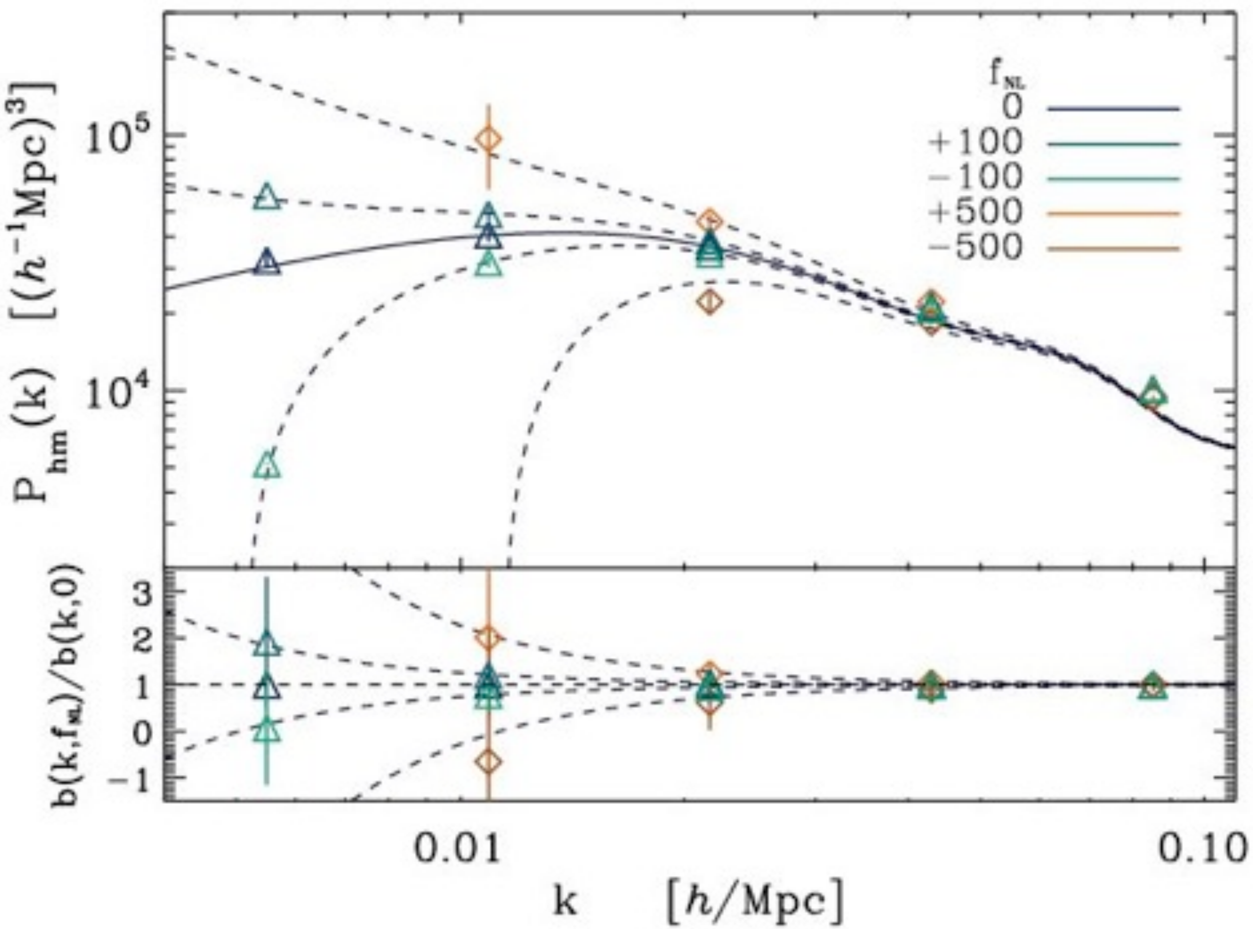


figure credit: Bill Keel

Simulations and theory both say: large-scale bias is scale-independent
(theorem if halo abundance is function of local density)

Scale dependence of NG halo bias

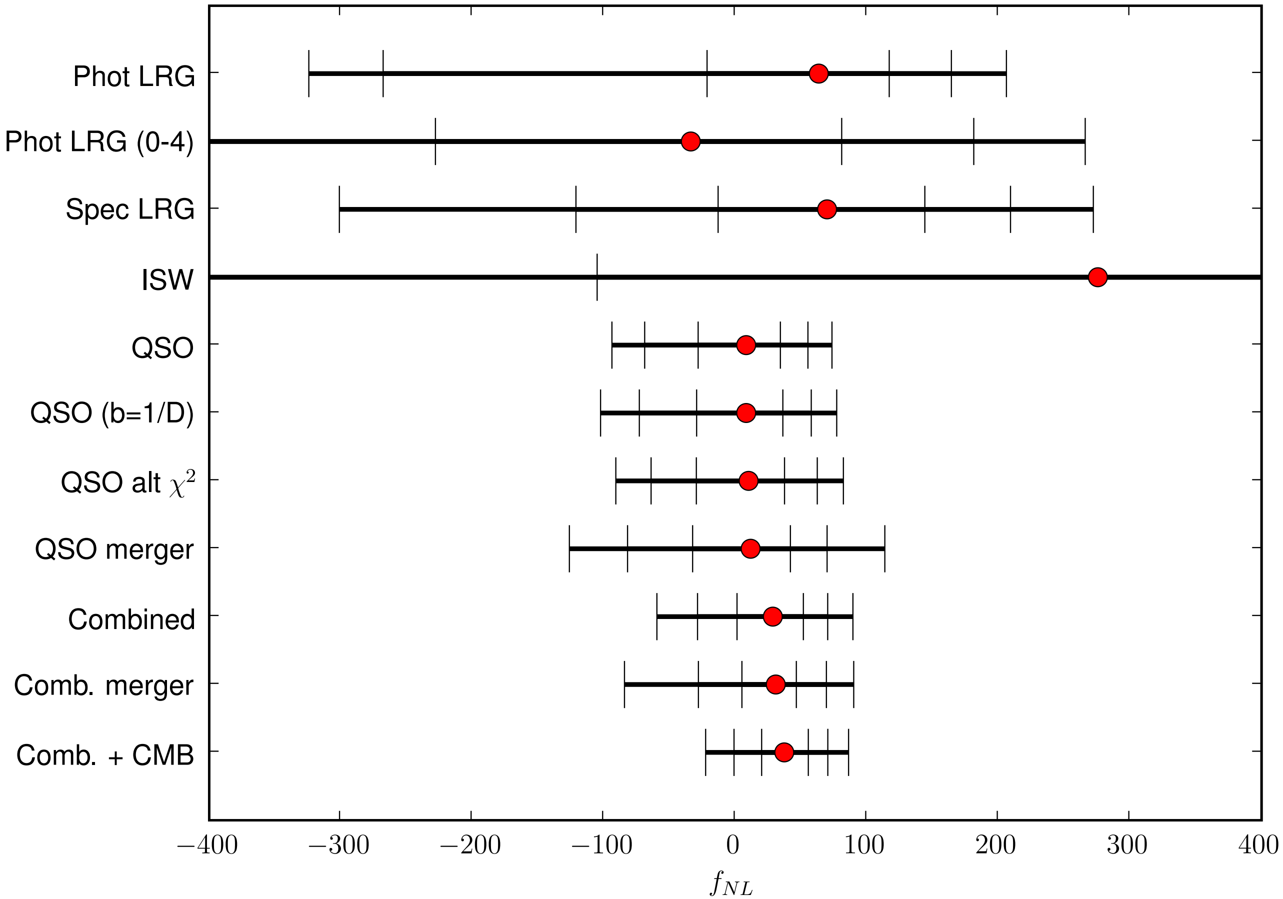


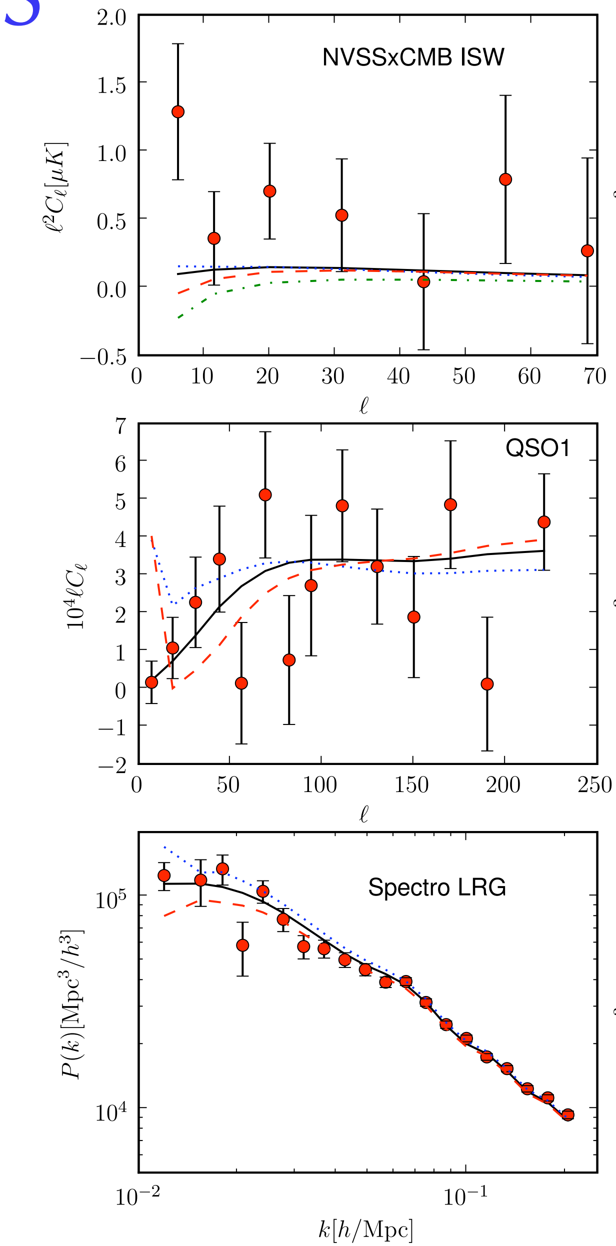
$$b(k) = b_{\mathrm{G}} + f_{\mathrm{NL}} \frac{\mathrm{const}}{k^2}$$

Verified using a variety of theoretical derivations and numerical simulations.

Dalal, Doré, Huterer & Shirokov 2008

Constraints from **current** data: SDSS





f_{NL} = 8 +/- 30 (68%, QSO)

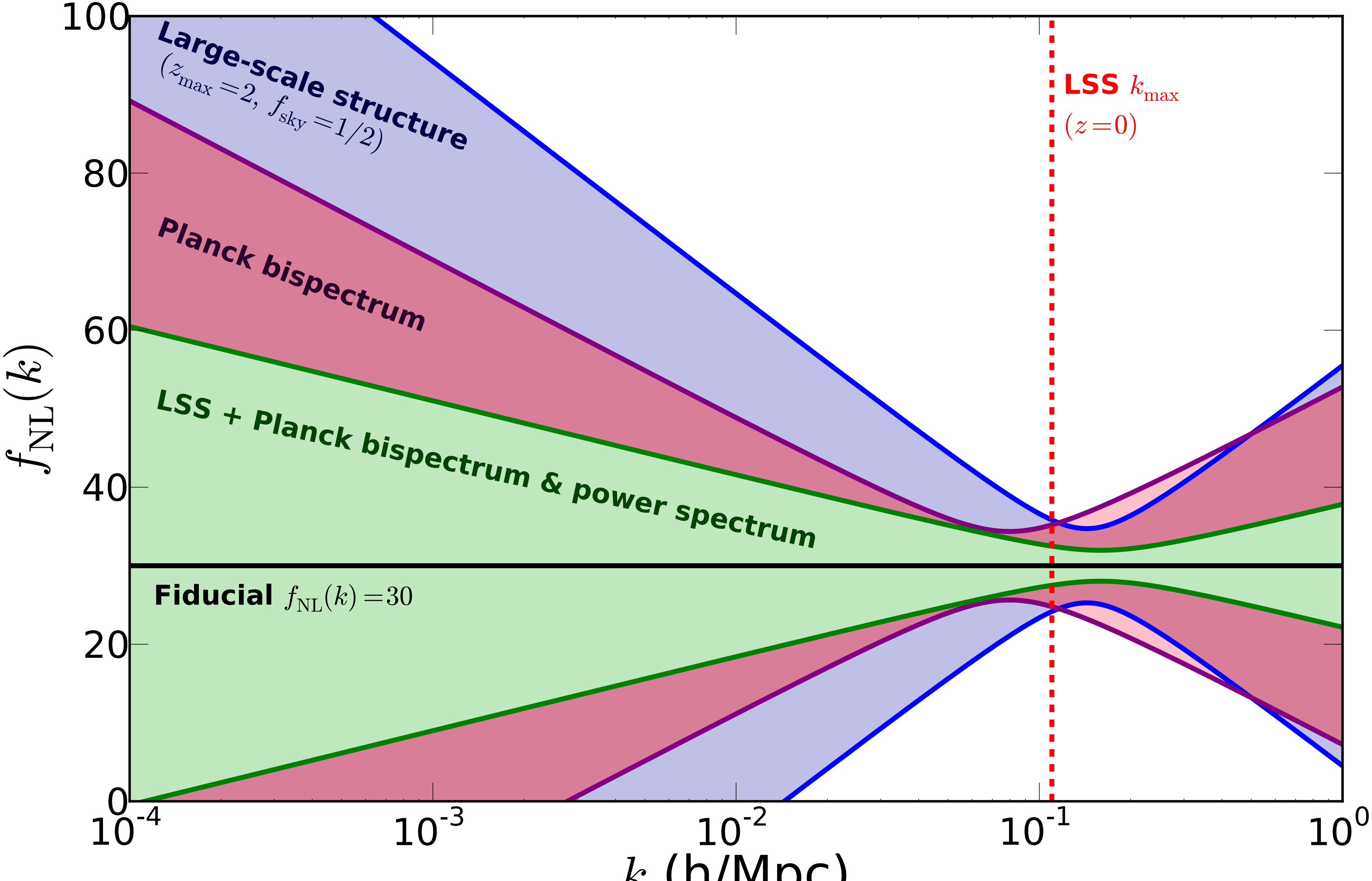
Slosar et al. 2008

f_{NL} = 23 +/- 23 (68%, all)

[**Future** data forecasts for LSS: $\sigma(f_{NL}) \approx O(\text{few})$
at least as good as, and highly complementary to, Planck CMB]

CMB, LSS, and CMB+LSS **forecasts**

$$f_{\rm NL}(k) = f_{\rm NL}(k_*) \left(\frac{k}{k_*}\right)^{n_f}$$



Becker, Huterer & Kadota, in preparation